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A REVIEW OF CRASHWORTHINESS OF COMPOSITE AIRCRAFT STRUCTURES

by

C. Poon

National Aeronautical Establishment

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A REVIEW OF CRASHWORTHINESS OF COMPOSITE AIRCRAFT STRUCTURES

ÉTUDE SUR LA RÉSISTANCE À L'ÉCRASEMENT DES STRUCTURES D'AÉRONEF EN MATÉRIAUX COMPOSITES

by/par

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National Aeronautical Establishment/
Établissement national d'aéronautique

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SUMMARY

A review of major research activities in North America with respect to the crashworthiness of composite aircraft structures was performed with the goal of identifying potential Canadian contribution to R&D areas where effort would be required to complement the on-going programs in the United States. The areas reviewed included the crashworthiness design criteria of the U.S. Army; major experimental programs undertaken by the FAA, the U.S. Army, NASA, and Bell Helicopter Textron Inc. in the U.S., as well as the University of Toronto in Canada in developing crashworthiness design concepts for composite structures; and the capabilities of crash dynamics computer codes. Recommendations include a study on the effect of aircraft size on crashworthiness design requirements; the implementation of the KRASH code in Canada to establish commonality in analytical methods with major U.S. and European users; an investigation on the energy absorption capabilities of the design features for small aircraft containing composite and/or composite/hybrid structures; and a parametric study on the crashworthiness design of composite-to-composite and composite-to-metal joints.

RÉSUMÉ

Une étude des principales activités de recherche menées en Amérique du Nord sur la résistance à l'écrasement des structures d'aéronef en matériaux composites a été effectuée dans le but d'identifier les éléments de participation possible du Canada dans les domaines de recherches et développement où un effort serait requis pour appuyer les programmes réguliers des États-Unis. Les domaines étudiés comprennent les critères de conception de résistance à l'écrasement de l'U.S. Army; d'importants programmes d'expérimentation entrepris par la FAA, l'U.S. Army, la NASA et Bell Helicopter Textron Inc. aux États-Unis, de même que par l'University of Toronto au Canada visant à mettre au point des concepts de conception de résistance à l'écrasement pour les structures d'aéronef; et les possibilités d'exploitation des codes machines pour le calcul des forces dynamiques lors de l'écrasement. Les recommandations comprennent une étude de l'effet de la dimension des aéronefs sur les exigences de conception relatives à la résistance à l'écrasement; l'implantation du code *KRASH* au Canada pour uniformiser les méthodes analytiques avec les principaux utilisateurs américains et européens, une étude des capacités d'absorption d'énergie des caractéristiques de conception des petits aéronefs qui contiennent des structures en matériaux composites et (ou) en composites/hybrides; et une analyse paramétrique des conceptions de résistance à l'écrasement des joints composite sur composite et composite sur métal.

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KEYWORDS: Acceleration forces, composite structures, crash impacts, crashworthiness, DYCAST, energy absorption, failure modes, helicopter, KRASH, nonlinearity, post-crash integrity, small aircraft, structural joints, thermoplastics.

LIST OF ABBREVIATIONS

ACAP	Advanced Composite Airframe Program
AVRADCOM	Army Aviation Research and Development Command
BHTI	Bell Helicopter Textron Inc.
CFE	Self-Consistent Finite Element
D/t	Inside Diameter to Wall Thickness Ratio
DYCAST	Dynamic Crash Analysis of Structures
FAA	Federal Aviation Administration
GL/E	Glass/Epoxy
GR/E	Graphite/Epoxy
K/E	Kevlar/Epoxy
LMFE	Lump Mass Finite Element
NAE	National Aeronautical Establishment
NASA	National Aeronautical and Space Administration
NRC	National Research Council (Canada)
PEEK	Polyetheretherketone
SMI	Sypher:Mueller International Inc.
TC	Transport Canada
TDC	Transportation Development Centre
UTIAS	University of Toronto Institute of Aerospace Studies

A REVIEW OF CRASHWORTHINESS OF COMPOSITE AIRCRAFT STRUCTURES

1.0 INTRODUCTION

1.1 Background

The Transportation Development Centre (TDC) and the Director of Airworthiness, Transport Canada (TC) commissioned the Sypher:Mueller Inc. (SMI) to review the status of North American research and development in small aircraft crashworthiness. The object was to identify the potential for Canada to play a role in developing crashworthiness requirements for small aircraft and to develop a comprehensive R&D program which would contribute to the enhancement of the safety of small aircraft. The study was completed in July 1987 with the issue of Report TP8655E entitled "Small Aircraft Crashworthiness" by the TDC [1].

Following the research study, a seminar was held on March 9, 1988 under the joint sponsorship of the TDC and TC. The purpose was to explore the future focus of Canadian R&D activity in small aircraft crashworthiness, to develop a coordinated R&D program between government, industry, and the universities, and to enhance the joint R&D activities between Canada and the U. S. The seminar was attended by all sectors of the Canadian Aviation Community, including Transport Canada, National Research Council (NRC), Aerospace Industries Association of Canada, Canadian Aviation Safety Board, University of Toronto Institute of Aerospace Studies (UTIAS), Canadian Owners and Pilots Association, plus representatives of the United States Federal Aviation Administration (FAA), National Transportation Safety Board, and the General Aviation Manufacturer's Association. Upon the recommendation of the Canadian participants, a Small Aeroplane Crashworthiness R&D Committee was established under the initial sponsorship of TC and the National Aeronautical Establishment (NAE)/NRC. The role of the Committee is to coordinate and advise TC on the conduct of R&D for the improvement of crashworthiness of small aeroplanes which include normal, utility and aerobatic aeroplanes in Canada.

The first meeting of the Committee on June 1, 1988 established a task for SMI to develop a small aeroplane crashworthiness R&D plan based on the seminar proceedings and the conclusions and recommendations of the report TP8655E. In the second meeting on August 29, 1989, the Committee approved the draft report "Crashworthiness R&D Plan" prepared by SMI [2]. The report produced a list of five program areas. The program area with the highest priority dealt with Seats, Harnesses, and Floor Sub-Structures while the program area next in priority concerned Composite Materials and Structures. The Committee recommended the establishment of a working team consisting of technical staffs from TC and NAE to produce work statements in these two program areas. To respond to the Committee's recommendation, the Structures and Materials Laboratory of NAE initiated two in-house reviews of the research work performed in these two program areas. This report presents the review of the work done to address the crashworthiness aspects of composite structures.

1.2 Report Organization

Most of the work covered in this review was performed in the U.S. under the sponsorships of the FAA, U.S. Army and NASA. This review excluded the historical evolution of regulatory requirements and development of accident analysis in small aircraft crashworthiness since these two topics are well covered in Report TP8655E [1].

A general, comprehensive overview of crashworthiness research activities in both the U.S. and Canada is provided in Report TP8655E [1]. This present review attempts to avoid duplications and focuses on technical details of the research activities with respect to crashworthiness of composite airframe structures. A description of the development of the Aircraft Crash Survival Design Guide [3] by Simula Inc. for the U.S. Army and highlights of crashworthiness design criteria of the MIL-STD-1290A [4] are given in Section 2. Although the criteria discussed are considered significantly more demanding than those required in the Federal Aviation Regulations, they are regarded as extremely valuable in developing new crashworthiness standards including those for new materials. Section 3 presents an overview of major research activities addressing the energy-absorbing characteristics of composite structures. It includes programs undertaken by the FAA, Bell Helicopter Textron Inc. (BHTI), U. S. Army and NASA that range from testing of simple cylinders to complex crash testing of full-scale structures. State-of-the-art computer codes that are capable of crash simulation of composite structures are discussed in Section 4. The last section is devoted to conclusions and recommendations.

2.0 CRASHWORTHINESS DESIGN CRITERIA

The Aircraft Crash Survival Design Guide [3] was prepared for the Safety and Survivability Technical Area of the Applied Technology Laboratory, U.S. Army Research and Technology Laboratories of the U.S. Army Aviation Research and Development Command (AVRADCOM) by Simula Inc. A major portion of the data contained in the Design Guide was taken from the U.S. Army sponsored research in aircraft crashworthiness conducted from 1960 to 1979. Since its initial publication in 1967, the design guide has been revised several times to incorporate the results of continuing research in crashworthiness technology. The fourth revision of the Design Guide contains a comprehensive treatment of all aspects of aircraft crash survival documented up to 1979 and its design criteria were used to formulate the latest revision of the U.S. Army's aircraft crashworthiness military standard MIL-STD-1290A(AV), published in September 26, 1988. Highlights of the design criteria contained in MIL-STD-1290A(AV) [4] are presented in the following paragraphs.

The goal of a crashworthiness design of an airframe structure is to prevent occupant fatalities and minimize the severity of injuries in survivable crash impacts. Survivable crash impacts were defined as those in which the forces transmitted to the occupant through the seat and restraint system do not exceed the limits of human tolerance to abrupt accelerations and in which the structure in the occupant's immediate environment remains substantially intact to the extent that a livable volume is provided for the occupants throughout the crash sequence. Typical Army survivable crash impact conditions are shown in Table 1. To achieve this goal, the airframe must be designed to maintain structural

integrity and a livable space for the occupants. The airframe should also be designed to possess high roll-over strength and high retention strength for large mass components. In order to minimize the effects of post-crash hazards, the structure should be designed to maintain the integrity of normal exits for emergency egress and provide protection against flammable fluid systems.

Energy-absorbing features are required to prevent excessive and injurious acceleration (G) forces from being transmitted to the occupants under the crash impact conditions given in Table 1. The limits of human tolerance to abrupt accelerations can be found in Volume II of the Aircraft Crash Survival Design Guide [3]. The forward fuselage structure should be designed to absorb energy during longitudinal impacts and to minimize soil plowing. In addition, the floor structure must be designed to maintain sufficient strength througthout the crash to carry the loads applied by occupants, seats and cargo restraint systems. A crushable sub-floor structure should be incorporated to absorb energy in vertical crash impacts. Energy-absorbing seats and proper occupant restraint systems should be provided to improve survivability and minimize the severity of injuries. The wings should be designed to possess frangible characteristics such that they break free from the fuselage under high impact loads. The landing gear should be designed to provide energy absorption to reduce the vertical velocity of the fuselage.

In order to satisfy the crashworthiness design criteria discussed, a total systems approach which includes a strong protective shell to protect the occupants from crushing as well as energy-absorbing components to prevent injurious G forces must be adopted. It is important to demonstrate that in replacing metals by composite materials in aircraft structures, the capability to absorb energy and to maintain post-crash integrity is not compromised. In the following section, the review is focused on the research activities in the development of energy-absorbing composite structures which demonstrate compliance with the crashworthiness design criteria.

3.0 ENERGY-ABSORBING COMPOSITE STRUCTURES

Polymer-based fiber composite materials offer significant benefits over metallic structures in reducing weight and cost as well as improving fatigue and corrosion resistance. However, these materials exhibit low strain-to-failure ranges compared to such metals as 2024 aluminium, a ductile metal that can tolerate rather large strains, deform plastically, and absorb a considerable amount of energy in the nonlinear region without fracture. Because of this difference between metals and composites, crash energy absorption with composites must come from innovative design to enhance stress-strain behaviour. Innovative design concepts involving notched corners, corrugated and tapered edge joints, and less stiff laminate layups were found to be effective in improving load-deflection characteristics of composite structures.

Assembly operations such as mechanical joining, adhesive bonding, co-curing, and other kinds of attachments contribute to crashworthiness. A further enhancement in energy absorption and post-crash integrity can be achieved by optimizing the design of joints. The design of composite joints is well known to be influenced by many parameters which affect

not only the strengths of the joint but also the failure modes [5]. Test data presented in the form of design curves that show the relationships between these parameters and joint strengths are commonly applied in empirical or semi-empirical methods for the optimization of joint designs. For crashworthiness considerations, the empirical relationships between these parameters and energy absorption are also required for the optimization of joint designs. A parametric investigation of adhesively bonded aluminium joints under impact-tension loading was undertaken jointly by the Alcan International Ltd. and NAE [6]. In the Alcan-NAE joint investigation, a conventional drop weight impact machine was modified to test adhesively-bonded coupons under tension loading. The effects of various parameters including curing conditions. surface treatment procedures, adhesive systems, and joint configurations on joint strength and energy absorption were investigated. The present review showed that a similar parametric investigation involving composite joints had not been undertaken.

Major research activities to develop design concepts for energy-absorbing helicopter and transport aircraft composite structures have been undertaken in the U.S. and other countries. Design concepts were evaluated through crash testing of composite test articles that ranged from simple cylinders to full-scale structures and the results were compared to those generated using metallic structures as benchmarks. The present review covered significant research activities undertaken by the FAA, BHTI, U. S. Army and NASA.

3.1 FAA Crash Dynamics Program

One major area of the FAA sponsored research in crash dynamics addressed crashworthiness considerations of composite materials [7]. The FAA's approach in assessing crashworthiness designs of composite structures is that the combination of composite materials' behaviour and designs must exhibit equal or better energy absorption than the metals which they replace. Key parameters which can be used as measures of performance for comparing composite materials with metals have been established (Figure 1). The parameters are specific energy, which considers energy and weight; load uniformity, which indicates the relationship between peak and average impact force; stroke ratio, which provides a measure of the effective use of materials; energy dissipation density, which indicates the degree of effectiveness in absorbing energy; ratio of dynamic to static forces, which indicates strain rate effects; and crash stress, which is related to the forces and area involved in the loading. The results of a study undertaken by NASA with respect to application of composite materials to transport category airframe structures [8] illustrated the manner in which designs and material behaviour affected these parameters.

In collaboration with NASA, the FAA performed drop tests of sections of narrow- and wide-body airplane frames [9], a full-scale drop test of a complete test article ('Laurinburg') [10], and a remotely piloted airplane crash test (Controlled Impact Demonstration test) [11]. Although these tests were on metallic structures, they generated test data which could be used as a benchmark against those obtained from similar tests on composite structures. Also in collaboration with NASA, the FAA sponsored the development of the computer codes KRASH and DYCAST for crash dynamics analysis of both metallic and composite structures. The characteristics of these codes will be discussed in Section 4.

3.2 Bell Helicopter Textron Inc. (BHTI) Research Programs

In a BHTI in-house research program, initial investigations of the crash impact behaviour of composite materials were focused on the testing of simple composite cylinders. Crush testing of cylinders made of graphite/epoxy (GR/E), Kevlar/epoxy (K/E), and fiberglass/epoxy (GL/E) was performed by Cronkhite [12] to determine basic compression failure modes and energy absorption of these composites. He found that both the GR/E and GL/E cylinders failed in a brittle fracturing mode while the K/E cylinders failed in a progressive folding mode much like a ductile metal. The GR/E material showed the highest specific energy absorption (energy absorbed per pound weight).

The BHTI in-house program continued to investigate various energy-absorbing subfloor design concepts [13]. Of the concepts investigated, a K/E sandwich structure was selected for the design and fabrication of crushable subfloors of composite airframes. This decision was based on the results obtained from design-support testing of small keel beam sections which indicated that the K/E sandwich construction demonstrated excellent stroke-to-length ratios of up to 80% before bottoming out, good energy-absorbing and load-limiting ability, good post-crushing structural integrity and no significant load rate sensitivity.

In a contracted R&D program conducted by BHTI for the Applied Technology Laboratory of the U.S. Army Research and Technology Laboratories (AVRADCOM), the energy-absorbing K/E sandwich subfloor structure was incorporated into two full-scale composite cabin test sections and drop tested [14]. The floor structure utilized a crush initiator or "triggering device" to prevent the occurrence of excessive peak loading prior to the onset of controlled-load crushing (see Figure 2). The composite cabins were derived from BHTI's Advanced Composite Airframe Program (ACAP) and were fabricated with K/E, GR/E and GL/E materials. The KRASH computer code was used to design the ACAP composite airframe to meet the crashworthiness requirements of the U.S. Army MIL-STD-1290 [15]. The requirement for vertical crash impact velocity specified in MIL-STD-1290 is 42 ft/s. Both cabin sections were actually drop tested at 30 ft/s. Since both cabin sections were not equipped with landing gear, it was justified to adopt a lower drop velocity by assuming that the landing gear had slowed the aircraft from 42 ft/s to 30 ft/s prior to fuselage contact.

The first cabin section was drop tested at a 30 ft/s vertical impact velocity and at a flat attitude with no pitch or roll. Floor and bulkhead mounted stroking seats and anthropomorphic dummies were installed to study the effects of the crash on a human occupant. The second cabin section was impacted at a 20 deg. roll attitude and at the same velocity as the first test. The dummies and stroking seats were replaced with 177-pound rigid lumped masses in the second drop test. Accelerations of the large masses were measured in both drop tests and displacements of the stroking seats were recorded in the flat drop test. In addition, high-speed motion pictures were used to record the cabin structure response.

Both cabin drop tests successfully demonstrated that the U.S. Army's crashworthiness requirements could be met by a composite airframe structure based on the excellent post-

test condition of the cabins' protective shell structure and the performance of the energy-absorbing components. The U.S. Army's Aircraft Crash Survival Design Guide [3] recommends that the vertical acceleration of the pelvis should not be above 23G for a duration of longer than 6 msec in order to minimize the probability of injury to the occupants. Both floor and bulkhead mounted seats stroked properly and attenuated the decelerative loads on the dummies to the noninjurious levels recommended by the Design Guide. However, the vertical acceleration of the floor exceeded the 23G level for about 30 msec. Therefore, without the stroking seats, the occupant would have probably experienced injurious decelerative loads during the crash impact. This demonstrated the effectness of adopting a systems approach in crashworthiness design in protecting the occupants: The fuselage structure served to maintain a protective shell, provide energy absorption, and retain the seats and large masses while the seat restrained the occupants, provided additional energy absorption, and controlled decelerative loads on the occupant to tolerable levels.

The computer codes KRASH and DYCAST were used to simulate the crash response of the composite cabin sections. Details of the KRASH and the DYCAST codes, which are widely used in crash dynamics analysis, and a brief assessment of the simulation capability of these two codes will be given in Section 4.

3.3 U.S. Army / NASA Research Programs

Farley of the U.S. Army Research & Technology Laboratories (AVRADCOM) investigated the energy absorption characteristics of selected composite material systems and compared the results with aluminium [16]. Cylindrical specimens were fabricated with both tape and woven fabric prepregs using GR/E, K/E and GL/E materials and 6061 aluminium. Both static compression tests and drop-weight impact tests were conducted. The cylinders were subjected to static or dynamic loading that was applied parallel to the axis of the cylinders. Chamfering one end of the composite cylinders was adopted as a crush initiator to prevent the excesssive buildup of peak loads at the onset of cylinder collapse and to facilitate the occurrence of subsequent controlled-load crushing of the cylinder. The results varied significantly as a function of material type and ply orientation. In general, the GR/E cylinders absorbed more energy than the GL/E or K/E cylinders for the same ply orientation. The $[0°/\pm 15°]$ GR/E cylinders absorbed more energy than the aluminium cylinders. GR/E and GL/E cylinders failed in a brittle mode and had negligible post-crushing integrity, whereas the K/E cylinders failed in an accordian (folding) buckling mode similar to the aluminium cylinders. The post-crushing integrity of hybrid composite cylinders was also investigated and found not to be significantly better that of the single material cylinders. Composite material systems investigated were found to be impact speed insensitive up to 23 ft/s. Farley concluded that quasi-static test results were applicable to low velocity impacts.

In a subsequent study, Farley [17] conducted static crushing tests on GR/E and K/E cylinders to examine the influence of specimen geometry on the energy absorption capability of composite materials. Cylinders with inside diameters ranging from 0.5 to 4 inches were subjected to end loading that was applied parallel to the axis of the cylinder. One end of each cylinder tested was chamfered to facilitate the initiation of the crushing process. The

inside diameter to wall thickness ratio (D/t) was determined to significantly affect the energy absorption capability. The GR/E and K/E cylinders exhibited a nonlinear and bilinear relation, respectively, between energy absorption and D/t ratio. The increase in energy absorption as D/t ratio decreased was found to relate to a reduction in interlaminar cracking. The energy absorption of K/E cylinders was determined to be geometrically scalable whereas that of GR/E cylinders was not scalable.

Farley [18] conducted further static crushing tests on cylinders to evaluate the influence of fiber and matrix maximum strain at failure on the energy absorption capability of graphite reinforced composite material systems. Composite material systems investigated were:

(1) Thornel 300/Fiberite 934 -- A low strain fiber in a low strain matrix.
(2) Thornel 300/Narmco 5245C -- A low strain fiber in a high strain matrix.
(3) Hercules AS4/Fiberite 934 -- A high strain fiber in a low strain matrix.
(4) Hercules AS4/Narmco 5245C -- A high strain fiber in a high strain matrix.

The material properties of the fiber and matrix materials used are presented in Table 2. The T300 and AS4 graphite fibers have similar extensional moduli although the AS4 fiber has approximately a 20% greater strain at failure than the T300 fiber. The 5245C matrix material has approximately a 100% greater strain at failure than the 934 matrix material. Test results shown in Figure 3 indicated that the fiber and matrix maximum strain at failure significantly affected energy absorption. The higher strain-at-failure system, AS4/5245C, exhibited the highest energy absorption capability among the four composite systems tested. All material systems tested exhibited typical failure modes of brittle fiber reinforced composite material systems. Two predominant failure modes were observed: the bending crushing mode and the fracturing crushing mode. The former mode is a lower energy-absorbing mode. For T300/5245C and AS4/5245C, the crushing mode of was primarily a fracturing crushing mode. The crushing characteristics demonstrated by these four material systems suggested that to achieve the maximum energy absorption from a particular fiber, the matrix material must have a greater strain at failure than the fiber.

Farley's work described earlier did not investigate very high ultimate strain material systems. In an extensive collaborative effort with NASA, Farley, et al. [19] conducted static crushing tests on cylindrical specimens to evaluate the effects of very high ultimate failure strain fibers (> .015 strain) and toughened matrices relative to energy absorption. In addition, the effects of fiber stiffness, fiber volume fraction, lamina stacking sequence, and hybrid material systems were assessed. The materials investigated and their mechanical properties are shown in Table 3.

Static tests were conducted on cylinders fabricated from AS6/F185 and AS6/HST-7. The ultimate failure strain of the AS6 fiber is 17% higher than that of the AS4 fiber used in Reference 18. The F185 matrix has approximately 600% greater failure strain than the 5245C matrix used in Reference 18. The HST-7 matrix is an interleafed system where the base matrix has similar properties as the 934 matrix while the interleafing material is a high strain adhesive. Test results shown in Figure 4 indicate that the higher failure strain material systems, AS6/F185 and AS6/HST-7, have lower energy absorption than the

AS4/5245C used in Reference 18. The cylinders fabricated from AS6/F185 with ply orientations of $[\pm 45°]_6$ and $[\pm 75°]_6$ were found to exhibit a ductile folding mode similar to that of Kelvar reinforced composites and have post-crushing integrity. The folding mode for these two ply orientations was due to the suppression of the formation of interlaminar cracks in the high strain matrix. The AS6/HST-7 material exhibited better energy absorption capability than the AS6/F185 material but it exhibited less energy absorption capability than the AS4/5245C material. The diameter of the AS6 fiber is smaller than that of the AS4 fiber. This factor was considered to be the primary cause for the lower compression strength of the two composite systems reinforced with the AS6 fibers when compared with the AS4/5245C system.

The investigation of Farley, et al. [19] also found that energy absorption was inversely proportional to fiber stiffness, the effect of fiber volume fraction on energy absorption was less than 10% for both GR/E and K/E material systems, lamina stacking sequence could influence the energy absorption of the material tested by a factor of 3, and hybrid composite systems composed of graphite and Kevlar reinforcements resulted in better energy absorption capability than aluminium while retaining post-crushing integrity.

The work carried out by Farely, et al. on cylinders has established that composite material systems possess good energy absorption capability under compressive loadings. However, under tensile or bending conditions, structural integrity may be lost at initial fracture and energy absorption can be low. Under crash conditions, aircraft structural elements experience complex loadings which are not always compressive. Therefore, a need existed to examine generic composite structures under crash loadings.

Recognizing the limitations of compression testing on small cylinders and the need to generate test data under complex crash loadings, NASA and the U.S. Army initiated a joint reseach program to investigate the crashworthiness potential of composite materials by performing full-scale drop tests on generic composite structural elements. In this program, Boitnott, et al. [20] conducted drop tests on GR/E frames with a Z-shaped cross section (see Figure 5). The dimensions of the cross section shown in Figure 5 were typically used in designs proposed for fuselage structure of advanced composite transports. A diameter of six feet for the frames was chosen to reduce specimen fabrication costs and to facilitate testing. The complete circular frame was assembled from four 90° sections by using mechanical fasteners and splice plates.

These frames were drop tested onto a concrete floor to simulate the crash conditions shown in Table 4. Five tests were performed. In the first test, a 3/16 inch steel cable was attached across the horizontal diameter of the frame to represent the constraint of a floor on the lateral expansion of an impacted frame. In the second and the third tests, a 1-inch diameter aluminium tube was used to represent this constraint more accurately. In the first three tests, ten-pound masses were attached to the left and right sides of the frame at the frame-floor intersection to represent structural and/or seat/occupant loads on the frame. In the fourth test, the applied mass was increased to 100 pounds by replacing the aluminium bar with an 80 pound steel bar. In the fifth test, a semi-circular frame was constructed using the upper half of the fourth frame since no visual damage was observed and the strains measured in the upper halves of the frames used in previous tests were generally very low.

A steel bar similar to the one used in the fourth test but slightly longer was used to simulate the floor constraint and to provide seat/occupant mass. In the first two tests, the frames were oriented so that impact occurred in the lower half of the frames at a splice plate. In subsequent tests, the frames were rotated 45° so that impact occurred in the lower half of the frames at a location midway between splice plates. Accelerometer, strain gauge, and high-speed photographic measurements were made and these data were used to characterize the impact behaviour of frames with different masses to represent structural or seat/occupant masses.

Failures of all GR/E frames tested involved complete separations through the cross section in the lower half of the frames. In the first two tests which involved impacts at a splice plate, failures of the lightly loaded composite frames were confined to an area 15° to the right of the impact point. In the third test which involved impact at a location midway between the splice plates, the lightly loaded frame suffered failure at the impact point. In the last two tests which involved impacts at a location midway between the splice plates of the more heavily loaded frames, the frames failed first near the impact point and then subsequently failed once on the left side and twice on the right side of the impact point (see Figure 6).

Typical filtered acceleration pulses measured at the frame-floor intersection for frames 2 and 5 are shown in Figure 7. Peak floor level accelerations of 63 G's and 15 G's were determined for frames 2 and 5 respectively. The maximum dynamic load at the floor level on each of the frames may be determined by multiplying the peak floor level acceleration by the floor mass. Using this method, the dynamic loads experienced by all the frames were found to be nearly constant for the greatly varying test conditions applied in this investigation.

All strain gauges indicated an initial pulse and initiation of frame failure occurred at this peak. For frames 1 and 2, circumferential flange strains (see Figure 8) were found to be highest near the impact point but were determined not to be high enough to cause a material failure. Instead the frame failure was initiated by a local structural instability. Strains measured by the gauges mounted on the flanges and web of frames 3 and 4 depicted the complexity of the structural deformations as a result of the impact. Strain values obtained near the impact point indicated that the strains were tensile on the inside flange and compressive on the outside flange. High radial bending strains measured by strain gauge rosettes on the web clearly showed that the original Z cross section was distorted. High in-plane shear strains near the impact point were also measured with these rosettes. In general, low strains were measured in the upper half of the frames.

The experimental floor level accelerations and strain values were used to calibrate the results obtained from an analysis of the response of the frames using the finite element code DYCAST. A review of the DYCAST code and its qualification against crash test results of aircraft structures will be presented in Section 4.

4.0 CRASH SIMULATION OF COMPOSITE STRUCTURES

An analytical tool is very important to the aircraft designers who are involved in evaluating and optimizing the crashworthiness of aircraft structures. Using such a tool the designer can simulate the complex behaviour of the structures under various impact loads without resorting solely to expensive and time consuming scale model testing. In order to be cost effective, the analysis must adopt the simplest feasible mathematical model representation of the actual structural response under crash conditions, while maintaining an acceptable level of accuracy. Because of the complexity of the problem, computer techniques are required to adequately address large deflections, nonlinear material response, local buckling and post-buckling behaviour, as well as component fractures. The following section will present the review of the simulation capability of three computer codes; two of the codes, the KRASH and DYCAST codes, have been developed in the U.S., while the third code has been developed at the UTIAS in Canada.

4.1 Computer Code KRASH

Under contract to the U.S. Army at the onset of the 1970's, the computer code KRASH was developed by the Lockheed California Company to provide an analytical capability to determine helicopter structural dynamic responses to multidirectional crash impact forces [21]. This analytical capability was required to support crashworthiness design trade-off studies. Subsequent to the U.S. Army's sponsored efforts, KRASH was upgraded under an FAA contract and its capability was directed toward the analysis of light fixed wing aircraft subjected to crash impact conditions [22]. The upgraded version is called KRASH79 and contains many new features while retaining its original concept. The completion of the FAA sponsored research in 1985 [23] has resulted in the current version, denoted KRASH85, which is capable of simulating crash scenarios of transport category aircraft. A comparison of the pertinent features of the three KRASH versions is shown in Table 5.

The computer code KRASH [24] can be used to perform a nonlinear transient response analysis to simulate the crash impact behaviour of any arbitrary three-dimensional structure. The analysis includes both geometric and material nonlinear structural behaviour capability. KRASH is often referred to as a "hybrid" analysis method because it generally requires input data derived from other analyses or tests since the structure is represented in a rather coarse manner using nonlinear beam and spring structural elements and lumped masses. The code integrates the Euler equations of motion of the lumped masses connected together by the beam members, each with six degrees of freedom, and computes the time histories of accelerations, velocities, and displacements. In addition, using small deflection linear analysis or large deflection plastic analysis, the internal beam forces, shears, moments and torsions are computed. The loads and deflections of the external springs used to simulate those portions of the aircraft coming into contact with the ground are also determined.

For the design of crashworthiness structures, the appropriate KRASH code is often used in conjunction with a conventional finite element program such as NASTRAN. For example, in the design of the composite cabin sections in Reference 14, KRASH85 was used

for the dynamic analysis of the cabin drop test conditions and NASTRAN was used for determining internal loads required for strength analysis (see Figure 9). The NASTRAN analysis was conducted using load factors from KRASH85 based on a "snapshot" of the dynamic loads at points in time when the loads were critical. The strength analysis performed using the NASTRAN internal loads was used for sizing the structure above the floor of the cabin where the deformation behaviour was expected to be mainly elastic. The sizing of the crushable subfloor structure was based on energy absorption and load attenuation requirements from the KRASH85 analysis using load-deformation characteristics of key energy absorbing components derived from design support test data.

During the course of the development of the KRASH codes, extensive comparisons have been made between test and analysis results, both by Lockheed and various other users [11, 21, 25-38]. A partial list of configurations and test conditions for which correlations have been performed is shown in Table 6. Furthermore, KRASH has been applied by numerous aircraft manufacturers to evaluate a wide range of design configurations. The development of KRASH has been greatly benefited from, and been accelerated by the positive cooperation of an international user community. For example, as noted in Reference 38, the KRASH79 code was modified by Aerospatiale to adapt to specific requirements and Lockheed, in collaboration with Aerospatiale, included several of the changes in the KRASH85 code. The feedback from KRASH users continues to be the best source of updating, improving and expanding the code as an analytical tool to support design trade-off studies. While efforts are continuing to expand its capability and applicability, the current usage of the KRASH code has indicated that a satisfactory level of acceptance has been achieved.

4.2 Computer Code DYCAST

DYCAST (Dynamic Crash Analysis of Structures) is a nonlinear, dynamic, finite element computer code developed by the Grumman Aerospace Corporation with principal support from NASA and the FAA as part of the combined NASA/FAA program for aircraft crashworthiness [39]. This code has the capability of modelling stringers, beams, bulkheads, and structural surfaces such as skins fabricated from isotropic as well as orthotropic materials. In order to provide the above modelling capability, the DYCAST code maintains a basic element library consisting of stringers with axial stiffness; beams with axial, two shear, torsion, and two bending stiffnesses; isotropic and orthotropic membrane skin triangles with in-plane normal and shear stiffnesses; isotropic plate bending triangles with membrane plus out-of-plane bending stiffnesses; and nonlinear springs with axial stiffness and a user specified load-deflection curve. The last element type can be used as either an elastic, dissipative or gap element. Under crash loadings, the changing stiffnesses in the structure are accounted for by plasticity (material nonlinearities) and very large deflections (geometric nonlinearities). The material nonlinearities are accommodated for by one of the three elastic-plastic options available in the code. Geometric nonlinearities are handled in an updated Lagrangian formulation. The stiffness variations due to structural failures are computed based on a failure option which is imposed automatically whenever a criterion for failure strain of the material is met or manually set by the user. The overall accuracy and computational cost of the simulation depends on the number of elements and degrees of freedom used. Refining the model may improve simulation accuracy, but always

drives up the costs. Therefore, the analyst must have sufficient expertise in modelling the structure for the nonlinear crash analysis in order to produce sufficiently accurate results within acceptable time and cost restraints.

The total cost of an analysis is composed of the labour involved in creating the model and evaluating the results and the cost of using the computer. Based on the experience of Winter, et al. [40], a first time full vehicle finite element model could require up to four person-months of effort to prepare and verify, depending on the model size and complexity. However, after the first time model is complete, it can be modified easily and at small cost, enabling the investigation of the effects of structural modifications. The computational costs are also dependent on model size and complexity. For a linear stress and vibration analysis, a finite element model could contain more than 20,000 degrees of freedom. Such a model would probably have already existed for the conventional design and analysis of the structure. However, the use of such an existing model, instead of creating a new one especially prepared for crash analysis, could save much time and labour in model preparation, but because of the limitations of current computers, a nonlinear dynamic analysis of this type of model using the DYCAST code is currently not feasible because of the computer time required. The optimal model size for a nonlinear finite element problem is therefore greatly dependent on the speed and memory capacity of the computer. Again based on the experience of Winter, et al. [40], a model having between 2000 and 3000 degrees of freedom and requiring several thousand time steps could complete the analysis overnight on the vector computers, such as the Cray-1 and the Cyber 205, using an in-core solution with a memory of 2 million words. Larger problems or smaller computer memory capacity and speed will require restart runs and longer time to complete the analysis. It is obvious that the finite element model must be designed to fit the available computer resources and includes all the important details for an accurate crash simulation.

In order to model the structure within available computer resources and produce accurate results, the DYCAST code allows the use of simple nonlinear spring elements to model crushable, energy absorbing components which exhibit extremely nonlinear behaviour. The advantage is that instead of requiring a large number of plate elements involving several thousand degrees of freedom for each collapse zone, only one degree of freedom is added for each nonlinear spring. However, this hybrid method requires the analyst to specify the expected large deformation behaviour by providing an input curve of load vs deflection or moment vs rotation generated by conducting component testing.

Applications of the DYCAST code include crash simulations of an aircraft fuselage subfloor [41], composite helicopter cabin sections [14], composite fuselage frames [20], an aircraft seat [42], and transport fuselage sections of the joint FAA/NASA Controlled Impact Demonstration test [30]. Of relevant interest to the present review is the accuracy of the crash simulation of composite structures using the DYCAST code. As mentioned earlier, the DYCAST analytical results were compared with the test results of the crash testing of the composite fuselage frames in the joint U.S. Army/NASA program [20]. As noted in Reference 20, only fair correlation was obtained between predicted and experimental frame-floor level accelerations. Frame response predicted by the DYCAST analysis showed significant sensitivity to moderate changes in the failure strain. Additional analytical studies are required to assess further the capabilities and possible improvements needed to analyze

composite structural elements using the DYCAST computer code.

As mentioned earlier, both the KRASH and DYCAST computer codes were evaluated in the BHTI research program on composite helicopter fuselage technology [14]. These two codes were used to simulate the crash responses of the full-scale composite cabins under flat drop test and 20° roll drop test conditions. The analysis results obtained from these codes were correlated with the drop test results. In addition, the KRASH code was used to design the composite cabins for the drop tests in accordance with the crashworthiness requirements of the MIL-STD-1290. Based on the good crash impact performance of the composite cabins and satisfactory correlations of analytical and test results, KRASH proved to be a useful and reasonably accurate analysis tool for the crashworthiness design of composite structures. The accuracy of the DYCAST predictions of damage, deformation, and accelerations was generally good for the flat drop test. However, the agreement between DYCAST and test results for the 20° roll drop test was mixed, with fairly good agreement in deformation and generally poor agreement in acceleration predictions.

4.3 Crash Dynamics Computer Code Developed at UTIAS

Under the joint sponsorship of the TDC and the Natural Sciences and Engineering Research Council of Canada, a comprehensive program was undertaken at the University of Toronto Institute of Aerospace Studies (UTIAS) to investigate, both analytically and experimentally, the dynamic behaviour of aircraft fuselage structures subjected to various impact conditions [43]. Two analytical models were developed to derive the motion equations, one based on a self-consistent finite element (CFE) technique [44] and the other on a more approximate, lumped mass finite element approach (LMFE) [45]. Extensive vertical drop and free-flight impact tests of scale model fuselage sections of stiffened aluminium were conducted using a pendulum gantry developed at UTIAS for a wide range of wing loads, angles of incidence and impact velocities [44]. Test data were obtained in terms of structural strains, G loads and high speed photography of the modes of dynamic collapse. Analytical results obtained by using the CFE and LMFE techniques demonstrated good correlations with experimentally generated G loads, dynamic peak strains and transient failure modes.

In a subsequent phase of the UTIAS program, partly funded by the Canadian Defence Research Establishment Suffield and the Natural Sciences and Engineering Research Council of Canada, a finite element computer model for analysing the crash response of stiffened composite fuselage structures was developed [46]. As demonstrated in Reference 46, the finite element computer model established by using a formulation based on Reissner/Mindlin plate theories can treat stiffened laminated shell buckling, large deflections, nonlinear material behaviour and element failure. Although experimental comparisons were not yet available, numerical results presented [46] for several test cases clearly showed that this code could determine transient displacements, velocities and accelerations. As reported in Reference 47, a composite fuselage model one meter in diameter by two meters in length was constructed and flight impact tests were to be conducted following a numerical analysis of the model for given load conditions. It was also stated that a non-destructive program was necessary to precede the final crash test to

optimize the amount of test data that could be obtained from such an expensive test article. However, a recent report indicated that flight impact tests of the composite fuselage had not been conducted [46]. Reference 46 was the most recent report which describes the flight impact test status of the composite fuselage at UTIAS.

5.0 CONCLUSIONS AND RECOMMENDATIONS

A review of major research activities in North America related to crashworthiness of composite structures was conducted. The intent of the review was to identify potential Canadian contributions to research on the crashworthiness of small aircraft containing composite structures and to propose research to complement the on-going activities in the U.S. This review effort encompassed the work undertaken or sponsored by the FAA, the U.S. Army, NASA, Bell Helicopter Textron Inc., Lockheed California Company and Grumman Aerospace Corporation in the U.S. and Transport Canada/Sypher:Mueller International Inc. and the University of Toronto Institute of Aerospace Studies in Canada.

The conclusions of this review have led to specific recommendations for further activities which will provide long and short term benefits in improving the crashworthiness of small aircraft containing composite structure. These proposed activities are concentrated on the dynamic impact testing of composite structures and on computational structural techniques where expertise already exists in Canada. Consequently, it is believed that these research activities have the potential to achieve their objectives. In order to maximize the chance of achieving the research objectives, these activities should be conducted in a coodinated manner involving several centers of expertise across Canada since the resources of most Canadian organizations are very stretched and too limited to make any effective contribution alone. The conclusions and the corresponding recommendations are provided as follows:

1. The research activities in crashworthiness design of composite structures pursued in the U.S. were highly focused on rotary wing and transport type aircraft. These research activities have generated a data base which will have applicability towards the establishment of crashworthiness design guidelines for small aircraft containing composite and/or composite/metal hybrid structures. However, it is considered extremely difficult if not impossible to directly relate crashworthiness design criteria and regulatory requirements developed from research on these types of aircraft to small aircraft containing composite and/or composite/metal hybrid structures because of size effects. Research on composite cylinders indicated that GR/E material sytems were not geometrically scalable. This review has shown that insufficient research is being directed, both in the U.S. and Canada, into the impact dynamics of small aircraft containing composite and/or composite/metal hybrid structures. Therefore, size effects on the crashworthiness behaviour of composite structures should be addressed before the application of the current crashworthiness design guidelines to composite small aircraft. Before the concern on size effects is resolved, full-scale crash testing of representative composite structures should be conducted.

2. This review indicated that a parametric study of the effects of the design variables affecting composite joints on failure mode, strength and energy absorption under dynamic loading had not been undertaken. Since a parametric study can provide useful insight and data for the optimization of composite joint design with respect to crashworthiness, it is highly recommended as an immediate research item.

3. This review has shown that the approach of using appropriate testing in conjunction with supportive analyses to assess design concepts of crash dynamics is feasible and could become a practical design methodology for composite small aircraft. The first recommendation will generate a data base to calibrate the analysis methods. State-of-the-art crash dynamics analysis codes reviewed include the KRASH, DYCAST and the code developed at the UTIAS. All three codes are capable of simulating crash behaviour of both metal and composite structures and have proved to be valuable analytical tools for crashworthiness design trade-off studies. The KRASH code is the most widely used code and has an international user base. Any R&D program would require the KRASH code to be commissioned in Canada because this will establish commonality in analytical tools with the U.S. as well as European users. Subsequent to the implementation of the KRASH code, an effort must be made to gain experience in using the tool for the crashworthiness design of small aircraft containing composite and/or composite/metal hybrid structures and to develop a suitable material data base which is of interest to the Canadian aviation community. This effort is necessary because the KRASH model is rather coarse and requires test data and considerable experience to simulate crash scenarios.

4. Since the KRASH code cannot provide the internal load distribution of a structure, a complementary structural analysis tool is required for strength prediction. Both the UTIAS and DYCAST finite element simulations allow a more detailed and complete representation of the structure but require considerable modelling setup time and computer run time. Further work is recommended to explore the possibility to use the two simulations to complement each other, that is, the KRASH code could be used for overall vehicle response and the UTIAS or DYCAST for modelling critical areas of the structure where a more detailed structural representation and analysis is required. This could lead to a more cost-effective analysis.

5. The capability of the UTIAS code to simulate the crash behaviour of composite structures has not been subjected to experimental verification. A comparison between the UTIAS code and other codes has not been conducted. In order to use the UTIAS code or to use the UTIAS code with KRASH for the design of crashworthy composite aircraft structures, the capability of the UTIAS code must be verified against experimental results. Also, it is considered worthwhile to compare the UTIAS code with DYCAST and KRASH.

6. This review clearly shows that the crashworthiness behaviour of an aircraft depends on the materials used, as well as the construction and the shape of the structural elements. Preferred materials in crash application must exhibit non-brittle behaviour so that energy is absorbed through plastic deformation and maintain post-crash structural integrity. Conventional GR/E and GL/E material systems were shown to

be brittle under crush loading. However, K/E as well as composite systems with high strain-to-failure graphite fiber and toughened thermoset matrices were found to exhibit ductile folding mode similar to aluminium and to possess post-crushing integrity. The energy absorption and failure mode were found to be affected by hybrid construction, lamina stacking sequence, lay-up, fiber stiffness, matrix strain at failure and fiber volume fraction. A crush initiator or "triggering device" resulting from chamfering the end of composite cylinders or corrugated web design with notched attached angles in crushable subfloor construction was found to be effective in preventing excessive buildup of peak loads before the onset of controlled-load crushing. Since small aircraft containing composite and/or composite/hybrid structures may exhibit different dynamic responses under crash conditions when compare with helicopters and transport type aircraft, it is important to catalogue the detail design features for small composite/hybrid aircraft and to investigate their energy absorption capabilities. This recommendation will lead to the establishment of design data bases for input to analytical models.

7. The U.S. Army MIL-STD-1290A should be used as a basis for the development of crashworthiness design guidelines for small aircraft containing composite structures. The data to be generated from the recommended research items described in this section would be useful for the modification of the design criteria contained in MIL-STD-1290A to suit the requirements for composite aircraft structures.

6.0 ACKNOWLEDGEMENT

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7.0 REFERENCES

1. Monroe, R. L. and McLeish, W., "Small Aircraft Crashworthiness," Technical Development Center Report TP8655E, July 1987.

2. Monroe, R. L. and McLeish, W., "Crashworthiness R&D Plan", Sypher:Mueller International Inc., to be published as a Transport Development Center Report.

3. Desjardins, S.P., Lannanen, D.H. and Singley, D.T., III, "Aircraft Crash Survival Design Guide," USARTL-TR-79-22A to -22E, Vol. I to V, 1980.

4. Military Standard, MIL-STD-1920A(AV), "Light Fixed- and Rotary-Wing Aircraft Crash Resistance," Department of Defense, Washington, D. C., 26 September 1988.

5. Poon, C., "Literature Review on the Design of Composite Mechanically Fastened Joints," NAE-AN-37, National Research Council Canada, Ottawa, February 1986.

6. Poon, C. and Farahbakhsh, B., "Impact Testing of Adhesively-Bonded Aluminium Joints," NAE-LTR-ST-1670, National Research Council Canada, Ottawa, June 1988.

7. Wittlin, G. and Caiafa, C., "Transport Airplane Crash Simulation, Validation and Application to Crash Design Criteria," Proceedings of the AGARD Conference on Energy Absorption of Aircraft Structures as an Aspect of Crashworthiness, Luxembourg, AGARD-CP-443, May 1988.

8. Jackson, A. C., "Transport Composite Fuselage Transmission," NASA CR 4035, December 1986.

9. "DC-10 Fuselage Drop Test Report," Report No. 7252-1, Arvin/Calspan Report prepared for the FAA Technical Center, Atlantic City, N.J., March 1984.

10. Johnson, D. and Garodz, L., "Crashworthiness Experiment Summary, Full-Scale Transport Controlled Impact Program," DOT/FAA/CT-85/20, June 1986.

11. Wittlin, G., "KRASH Analysis Correlation -- Transport Airplane Controlled Impact Demonstration Test," DOT/FAA/CT-86/13, December 1986.

12. Cronkhite, J. D. and Berry, V. L., "Crashworthy Airframe Design Concepts -- Fabrication and Testing," NASA CR3603, Washington, D.C., September 1982.

13. Cronkhite, J. D., Berry, V. L., and Winter, R., "Investigation of the Crash Impact Characteristics of Helicopter Composite Structures," USAAVRADCOM TR-82-D-14, Applied Technology Laboratory, U.S. Army Research and Technology Laboratories, Fort Eustis, Virginia, February 1983.

14. Cronkhite, J. D., "Design of Airframe Structures for Crash Impact," Proceedings of the American Helicopter Society Specialists' Meeting on Crashworthy Design of Rotorcraft, Atlanta, Georgia, April 1986.

15. Carnell, B. L. and Pramanik, M., "ACAP Crashworthiness Analysis by KRASH," American Helicopter Society Journal, Vol. 29, 1984, pp. 38-42.

16. Farley, G. L., "Energy Absorption of Composite Materials," Journal of Composite Materials, Vol. 17, May 1983, pp. 267-279.

17. Farley, G. L., "Effect of Specimen Geometry on the Energy Absorption Capability of Composite Materials," Journal of Composite Materials, Vol. 20, July 1986, pp. 390-400.

18. Farley, G. L., "Effect of Fiber and Matrix Maximum Strain on the Energy Absorption of Composite Materials," Journal of Composite Materials, Vol. 20, July 1986, pp. 322-334.

19. Farley, G. L., Bird, R. K. and Modlin, J. T., "The Role of Fiber and Matrix in Crash Energy Absorption of Composite Materials," Proceedings of the American Helicopter Society Specialists' Meeting on Crashworthy Design of Rotorcraft, Atlanta, Georgia, April 7-9, 1986.

20. Boitnott, R. L., Fasanella, E. L., Calton, L. E. and Carden, H. D., "Impact Response of Composite Fuselage Frames," SAE Technical Paper No. 871009, presented at the General Aviation Aircraft Meeting and Exposition, Wichita, Kansas, April 28-30, 1987.

21. Wittlin, G. and Gamon, M. A., "Experimental Program for the Development of Improved Helicopter Structural Crashworthiness Analytical and Design Techniques," Lockheed-California Company, USAAMRLDL-TR-72-72, Volumes I and II, May 1973.

22. Wittlin, G. and Gamon, M. A., "Full-Scale Crash Test Experimental Verification of a Method of Analysis for General Aviation Airplane Structural Crashworthiness," Lockheed-California Company, FAA Report FAA-RD-77-188, February 1978.

23. Gamon, M. A., Wittlin, G. and LaBarge, W. L., "KRASH85 User's Guide -- Input/Output Format," Lockheed-California Company, DOT/FAA/CT-85/10, May 1985.

24. Wittlin, G.,"Program KRASH: Evolution of an Analytical Tool to Evaluate Aircraft Structural Crash Dynamics Response," Proceedings of the American Helicopter Society Specialists' Meeting on Crashworthy Design of Rotorcraft, Atlanta, Georgia, April 1986.

25. Badrinath, Y. V., "Simulation Correlation and Analysis of Structural Response of a CH-47-A to Crash Impact," USARTL-TR-78-24, August 1978.

26. Mens, J., "Survey of Crashworthiness Achievements on Aerospatiale Helicopters," 41st Annual Forum, American Helicopter Society, Fort Worth, texas, May 1985.

27. Cronkhite, J. D. and Berry, V. L., "Investigation of the Crash Impact Characteristics of Helicopter Composite Structures," USAAVRADCOM-TR-82-D-14, February 1983.

28. Hayduk, R. J., Thomson, R. G., Wittlin, G. and Kamat, M. P., "Nonlinear Structural Crash Dynamics Analysis," SAE Paper 790588, April 1979.

29. Wittlin, G. and Lackey, D., "Analytical Modelling of Transport Aircraft Crash Scenarios to Obtain Floor Pulses," FAA Report DOT/FAA/CT-83/23, NASA CR 1666089, April 1983.

30. Wittlin, G. and Caiafa, C., "Transport Airplane Crash Simulation, Validation and Application to Crash Design Criteria," Proceedings of the AGARD Conference on Energy Absorption of Aircraft Structures as an Aspect of Crashworthiness, Luxembourg, AGARD-CP-443, May 1988.

31. Och, F., "Crashworthiness Activities on MBB Helicopters," Proceedings of the AGARD Conference on Energy Absorption of Aircraft Structures as an Aspect of Crashworthiness, Luxembourg, AGARD-CP-443, May 1988.

32. Nitschke, D. and Frese, J., "Crushing Behaviour of Helicopter Subfloor Structures," Proceedings of the AGARD Conference on Energy Absorption of Aircraft Structures as an Aspect of Crashworthiness, Luxembourg, AGARD-CP-443, May 1988.

33. Jarzab, W. and Schwarz, R., "Crashworthiness of Aircraft Structures," Proceedings of the AGARD Conference on Energy Absorption of Aircraft Structures as an Aspect of Crashwortxiness, Luxembourg, AGARD-CP-443, May 1988.

34. Mens, J. and Bianchini, J. C., "Computing Codes for Development of Helicopter Crashworthy Structures and Test Substantiation," Proceedings of the American Helicopter Society Specialists' Meeting on Crashworthy Design of Rotorcraft, Atlanta, Georgia, April 1986.

35. Pramanik, M. B. and Carnell, B. L., "Landing Gear Performance Simulation by KRASH Program," Proceedings of the American Helicopter Society Specialists' Meeting on Crashworthy Design of Rotorcraft, Atlanta, Georgia, April 1986.

36. Wittlin, G., "Aircraft Crash Dynamics: Modelling, Verification and Application," in Structural Crashworthiness, Edited by Jones, N. and Wierzbicki, T., Butterworth and Co., London and Boston, 1983, pp. 259-282.

37. Lamborn, L. C., "Crew Seat Stroke Requirements for Helicopter Rolled Attitude Impact Crashworthiness," Proceedings of the American Helicopter Society Specialists' Meeting on Crashworthy Design of Rotorcraft, Atlanta, Georgia, April 1986.

38. Soltis, S., Caiafa, C., Wittlin, G., "FAA Structural Crash Dynamics Program Update -- Transport Category Aircraft," SAE Paper 851887, Long Beach, CA., October 1985.

39. Pifko, A. B., Winter, R. and Ogilvie, P. L., "DYCAST -- A Finite Element Program for the Crash Analysis of Structures," NASA CR 4040, Washington, D.C., January 1987.

40. Winter, R. and Pifko, A. B., "Modelling Strategies for Finite Element Crash Simulation of Complete Vehicles," Proceedings of the American Helicopter Society Specialists' Meeting on Crashworthy Design of Rotorcraft, Atlanta, Georgia, April 1986.

41. Carden, H. D. and Hayduk, R. J., "Aircraft Subfloor Response to Crash Loadings," SAE Paper 810614, 1981.

42. Alfaro-Bou, E., Williams, M. S. and Fasanella, E. L., "Determination of Crash Test Pulses and their Application to Aircraft Seat Analysis," SAE Paper 810611, 1981.

43. Tennyson, R. C., Nanyaro, A. P., Teichman, H. C. and Hansen, J. S., "Crashworthiness of Light Aircraft Structures," Transport Canada Research and Development Centre Report TP3927, 1981.

44. Tennyson, R. C. and Hansen, J. S., "Study of the Crash Behaviour of Aircraft Fuselage Structures," in Structural Crashworthiness, Edited by Jones, N., and Wierzbicki, T., Butterworth and Co., London and Boston, 1983, pp. 218-258.

45. Tennyson, R. C., Teichman, H., Nanyaro, A. P. and Mabson, G., "Study of the Crashworthiness of Light Aircraft Structures," Proceedings of the Twenty Second Structures, Structural Dynamics and Materials Conference, AIAA/ASME/ASCE/AHS, Atlanta, Georgia, 1981.

46. Hansen, J. S. and Tennyson, R. C., "The Dynamic Behaviour of Stiffened Composite Fuselage Shell Structures," Proceedings of the AGARD Conference on Energy Absorption of Aircraft Structures as an Aspect of Crashworthiness, Luxembourg, AGARD-CP-443, May 1988.

47. Johnston, J., "Design and Fabrication of a Scaled Composite Fuselage Section," University of Toronto, M.A.Sc. Thesis, 1984.

CONDITION NUMBER	IMPACT DIRECTION (AIRCRAFT AXES)	OBJECT IMPACT	VELOCITY CHANGE Δ V (ft/sec)
1	Longitudinal (cockpit)	Rigid vertical barriers	20
2	Longitudinal (cabin)		40
3	Vertical*	Rigid horizontal surface	42
4	Lateral, Type I		25
5	Lateral, Type II		30
6	Combined high angle* Vertical	Rigid horizontal surface	42
	Longitudinal		27
7	Combined low angle Vertical	Plowed soil	14
	Longitudinal		100

* For the case of retracted landing gear the seat and airframe combination shall have a vertical crash impact design velocity change capability of at least 26 ft/sec.

TABLE 1 U.S. ARMY CRASH IMPACT DESIGN CONDITIONS (REF. 3)

MATERIAL DESCRIPTION	EXTENSIONAL MODULUS, E GPa (Msi)	DENSITY g/cm^3 (lb/in^3)	TENSILE FAILURE STRAIN
T300	231.5 (33.5)	1.75 (0.063)	0.012
AS-4	235.0 (34.0)	1.80 (0.065)	0.015
934	4.0 (0.58)	1.40 (0.046)	0.010
5245	3.8 (0.55)	1.25 (0.045)	0.020

TABLE 2 MECHANICAL PROPERTIES OF FIBER AND MATRIX MATERIALS USED IN REFERENCE 18

MATERIAL DESCRIPTION	EXTENSIONAL STIFFNESS, E GPa (Msi)	DENSITY ρ, g/cm^3 (lb/in^3)	ULTIMATE FAILURE STRAIN cm/cm (in/in)
FIBER			
T300	231.5 (33.5)	1.75 (0.063)	0.012
AS-6	235.0 (34.0)	1.80 (0.065)	0.018
P55	380.0 (55.0)	2.00 (0.072)	0.005
F75	520.0 (75.0)	2.00 (0.072)	0.004
Kevlar-49	124.0 (18.0)	1.44 (0.052)	0.028
MATRIX			
934	4.00 (0.58)	1.40 (0.050)	0.010
974	3.90 (0.57)	1.27 (0.046)	0.020
F185	2.00 (0.29)	1.26 (0.045)	0.130
HST-7*	3.80 (0.55)**	1.40 (0.050)**	0.010**

* Interleafed matrix material
** Appropriate values

TABLE 3 MECHANICAL PROPERTIES OF FIBER AND MATRIX MATERIALS USED IN REFERENCE 19

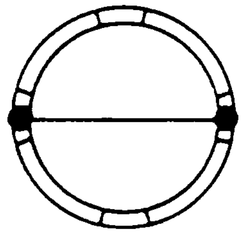
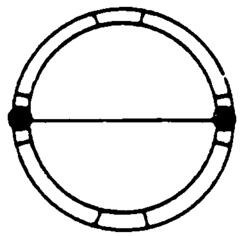
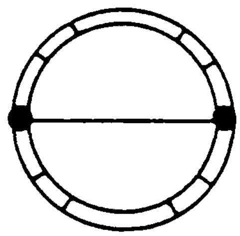
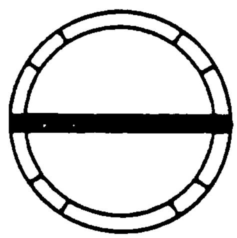
TEST NO.	IMPACT VELOCITY FPS	ADDED MASS LBS	CONFIGURATION	CENTER RESTRAINT
1	26.1	20		CABLE
2	27.5	20		TUBE
3	27.5	20		TUBE
4	20	100		BAR
5	20	93		BAR

TABLE 4 COMPOSITE FRAME TEST CONDITIONS (REF. 20)

FEATURES	KRASH	KRASH 79	KRASH 85
1. ENERGY DISTRIBUTION	YES	YES*	YES**
2. ELEMENT RUPTURE	YES	YES*	YES*
3. INJURY CRITERIA (DRI)[a]	YES	YES*	YES
4. PLOT CAPABILITY/SUMMARIES	YES	YES	YES**
5. VOLUME PENETRATION	YES	YES	YES
6. PLASTIC HINGE ALGORITHM	NO	YES	YES*
7. SHOCK STRUT	NO	YES	YES
8. FLEXIBLE AND/OR SLOPED TERRAIN	NO	YES	YES
9. ACCELERATION PULSE EXCITATION	NO	YES	YES
10. UNSYMMETRICAL BEAM REPRESENTATION	NO	YES	YES
11. STANDARD MATERIAL PROPERTIES	NO	YES	YES
12. EXTERNAL SPRING DAMPING	NO	YES	YES
13. MASS LOCATION PLOTS	NO	YES	YES
14. PRE- AND POST-DATA PROCESSING	NO	YES	YES
15. RESTART CAPABILITY	NO	YES	YES
16. SYMMETRICAL MODEL CAPABILITY	NO	YES	YES
17. CG FORCE MOTIONHISTORY	NO	YES	YES*
18. VOLUME CHANGE CALCULATIONS	NO	YES	YES
19. STANDARD NONLINEAR CURVES	NO	5	6
20. STIFFNESS REDUCTION FEATURE (KR)[b] APPPLICABLE TO DAMPING	NO	NO	YES
21. COMBINED FAILURE LOAD (LIC)[c]	NO	NO	YES
22. INITIAL BALANCE-NASTRAN	NO	NO	YES
23. TIRE VERTICAL SPRING	NO	NO	YES
24. ARBITRARY MASS NUMBERING	NO	NO	YES
25. EXTERNAL FORCE LOADING	NO	NO	YES
26. OLEO METERING PIN	NO	NO	YES
27. ADDITION OF DESCRIPTIVE NAMES TO IDENTIFY INPUT DATA	NO	NO	YES

* Enhanced one level, ** Enhanced two levels

[a] Dynamic response index [b] Stiffness reduction factor [c] Load interaction curve

TABLE 5 COMPARISON OF PERTINENT FEATURES OF THE THREE KRASH VERSIONS (REF. 24)

AIRCRAFT	GROSS WEIGHT (kg)	IMPACT VELOCITY (m/sec)			REFERENCE
		VERTICAL	LONGITUDINAL	LATERAL	
ROTARY WING					
Utility type	3909	7.0	–	5.6	21
Cargo type	11045	12.8	8.3	–	25
Multi-purpose	1727	6.0	6.0	–	26
Multi-purpose	1645	10.0	–	–	26
Composite substructure	1605	9.1	–	–	27
Composite substructure	1605	8.6	–	3.1	27
LIGHT-FIXED-WING					
Single-engine, high-wing	1091	14.0	21.3	–	22
Single-engine, high-wing	1091	6.7	21.7	–	22
Single-engine, high-wing	1091	14.9	21.3	–	22
Single-engine, high-wing*	1091	13.1	21.2	–	22
Twin-engine, low-wing substructure	248	8.4	–	–	28
TRANSPORT					
Medium size*	72272	5.5	5.24	–	29
Medium size	88636	5.3	79.2	–	11

* Test performed on soil; all other tests on rigid surface.

TABLE 6 KRASH EXPERIMENTAL VERIFICATION (REF. 24)

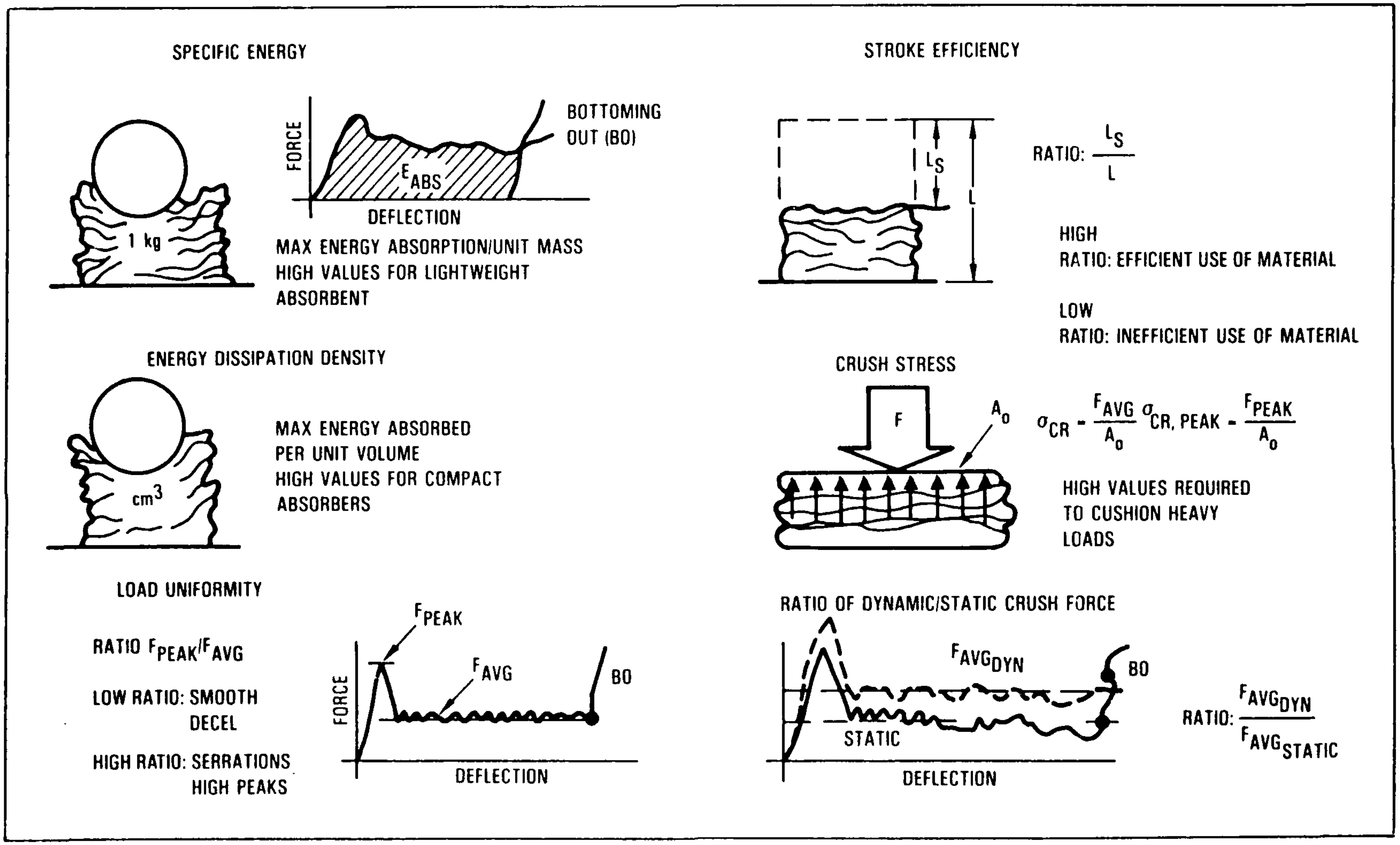


FIG. 1: KEY PARAMETERS FOR COMPARISON OF CRASHWORTHINESS PERFORMANCE (REF. 7)

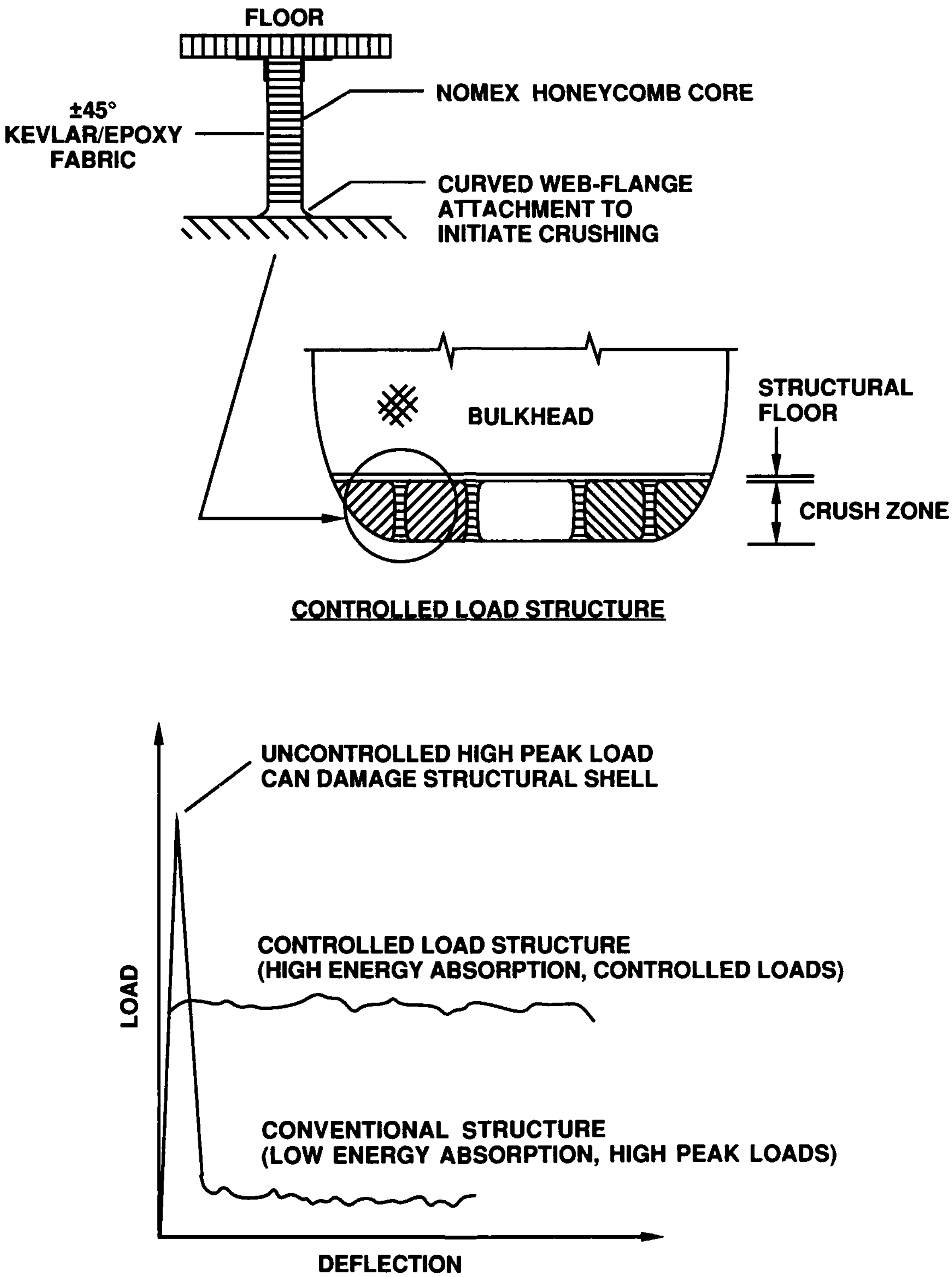


FIG. 2: LOAD-DEFLECTION CHARACTERISTICS OF CRUSHABLE SUBFLOOR STRUCTURE WITH "TRIGGERING DEVICE" (REF. 13)

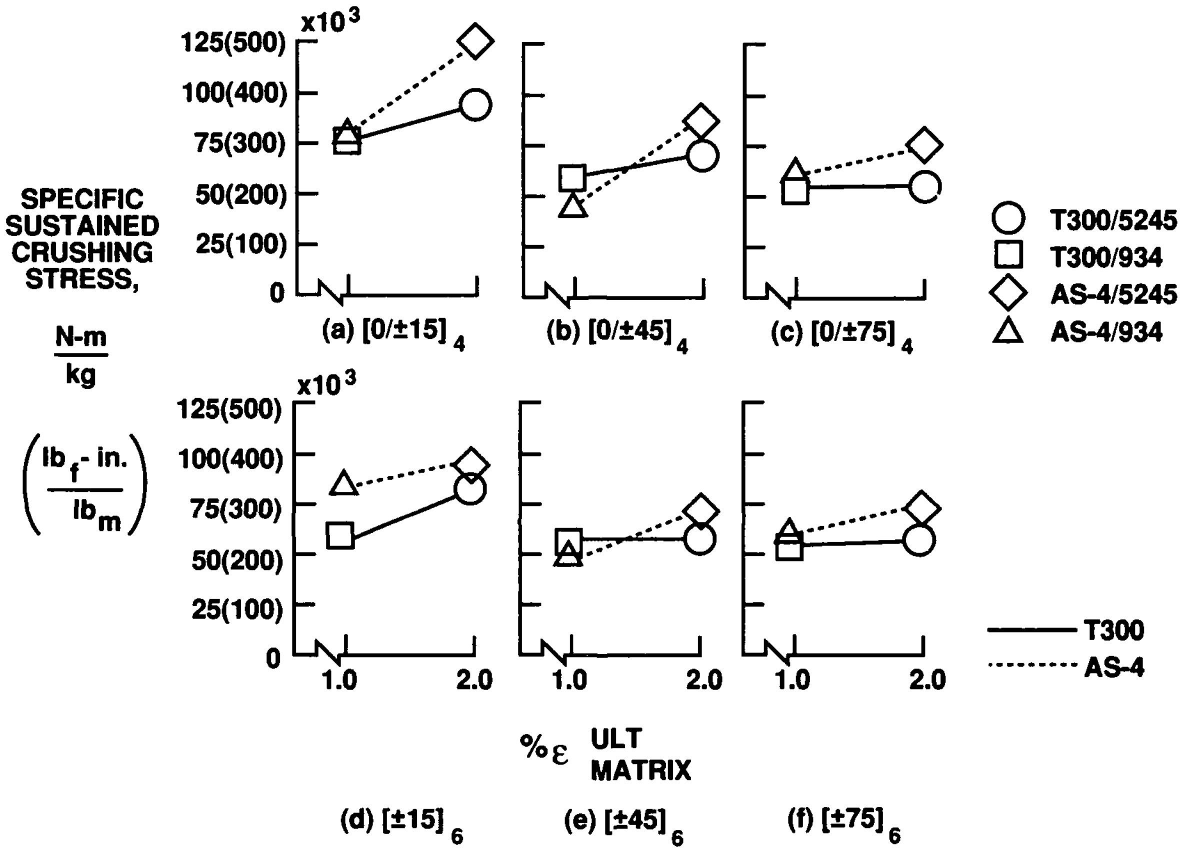


FIG. 3: EFFECT OF MATRIX FAILURE STRAIN ON THE ENERGY ABSORPTION OF GRAPHITE REINFORCED COMPOSITE MATERIALS(REF. 18)

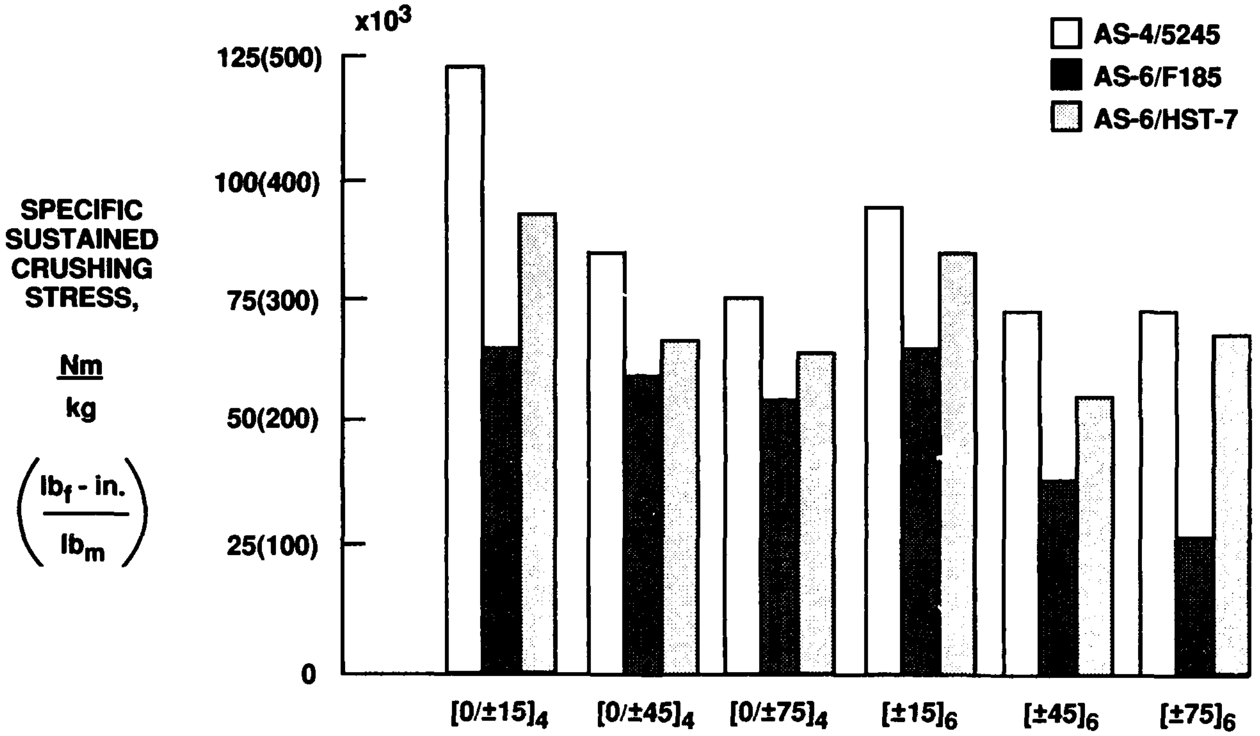


FIG. 4: ENERGY ABSORPTION OF AS-4/5245, AS-6/F185 AND AS-6/HST-7 COMPOSITE MATERIAL (REF. 19)

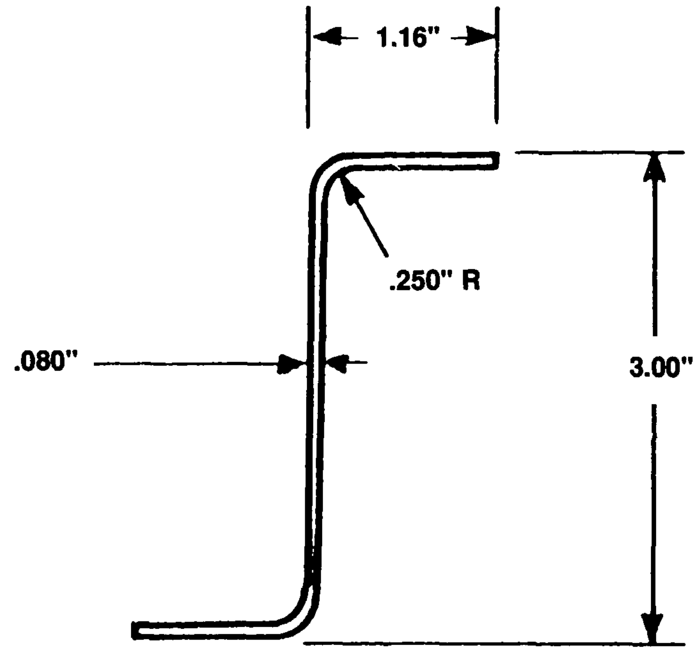


FIG. 5: GRAPHITE-EPOXY Z-SHAPED FRAME CROSS SECTION (REF. 20)

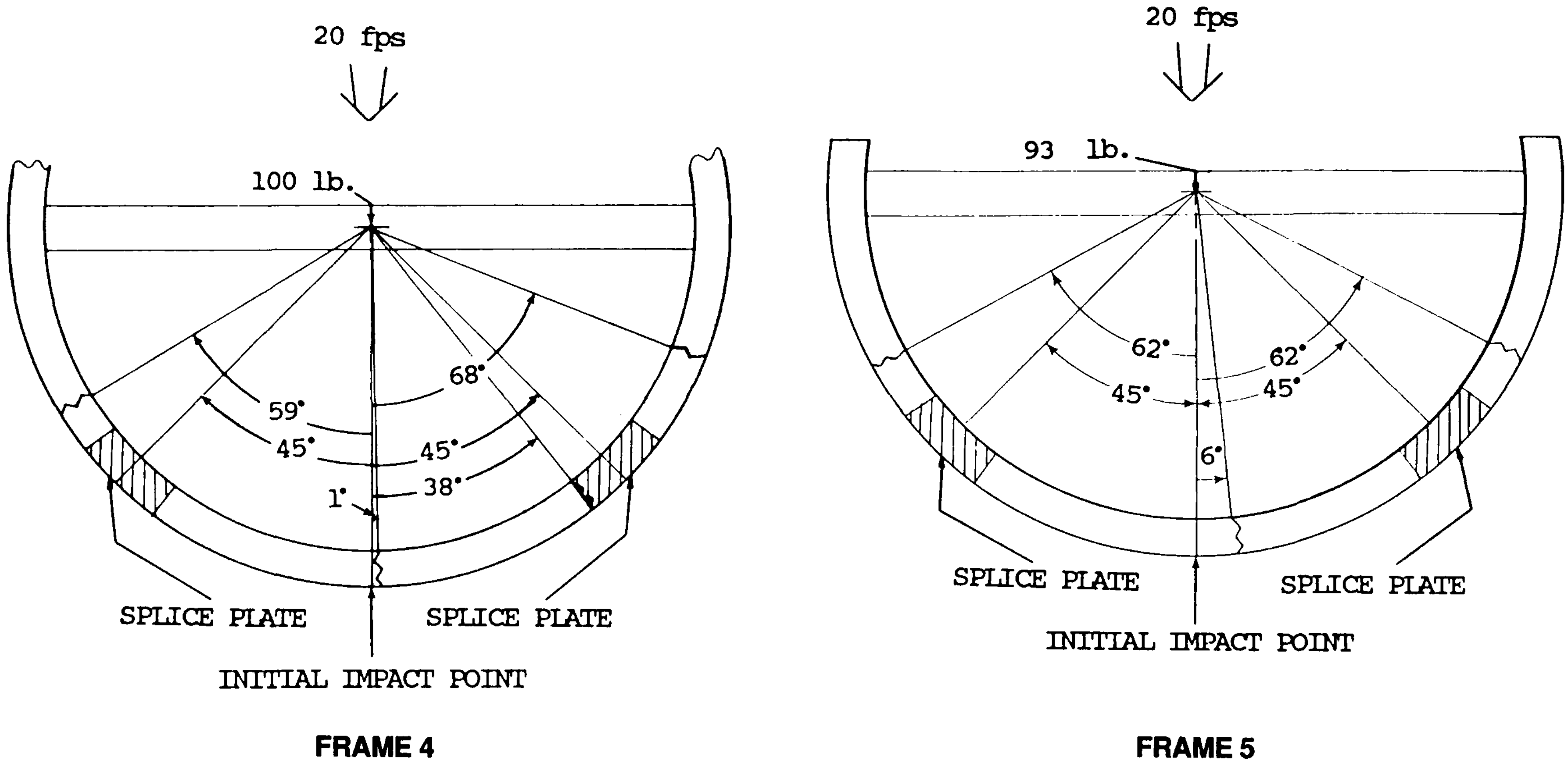


FIG. 6: FAILURE LOCATIONS FOR FRAMES 4 AND 5 (REF. 20)

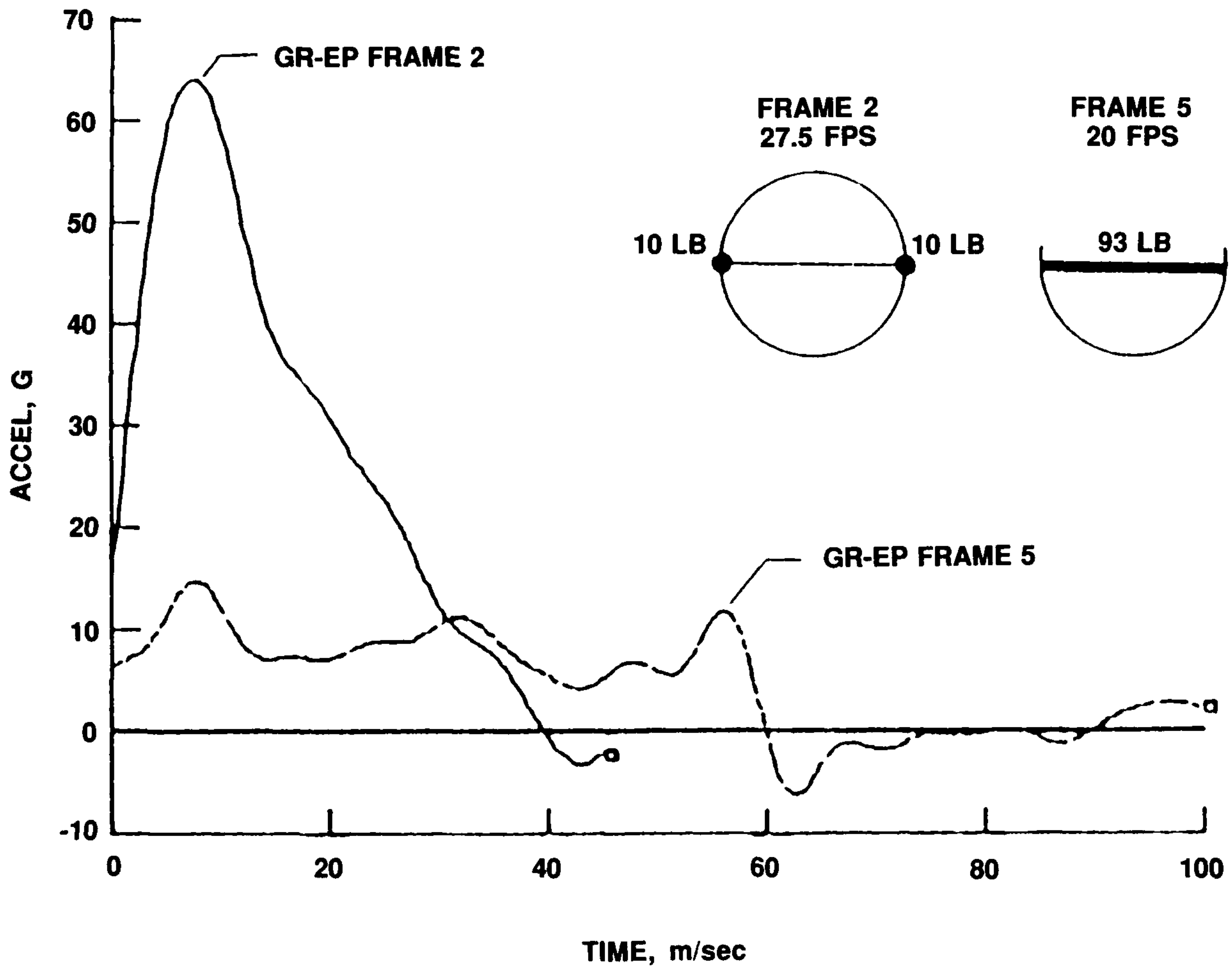


FIG. 7: FLOOR LEVEL ACCELERATION PULSE FOR FRAMES 2 AND 5 (REF. 20)

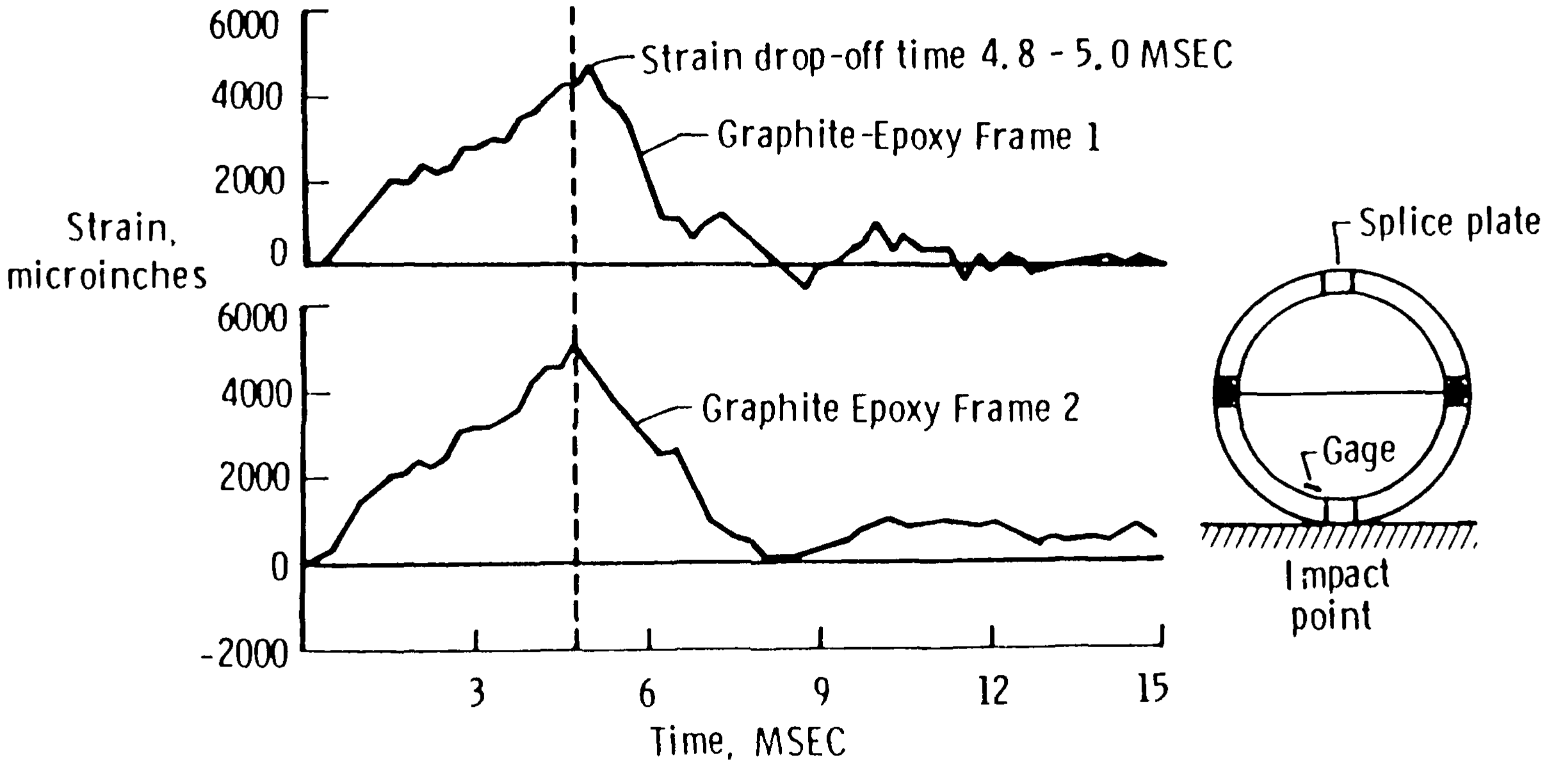


FIG. 8: CIRCUMFERENTIAL FLANGE STRAINS FOR FRAMES 1 AND 2 (REF. 20)

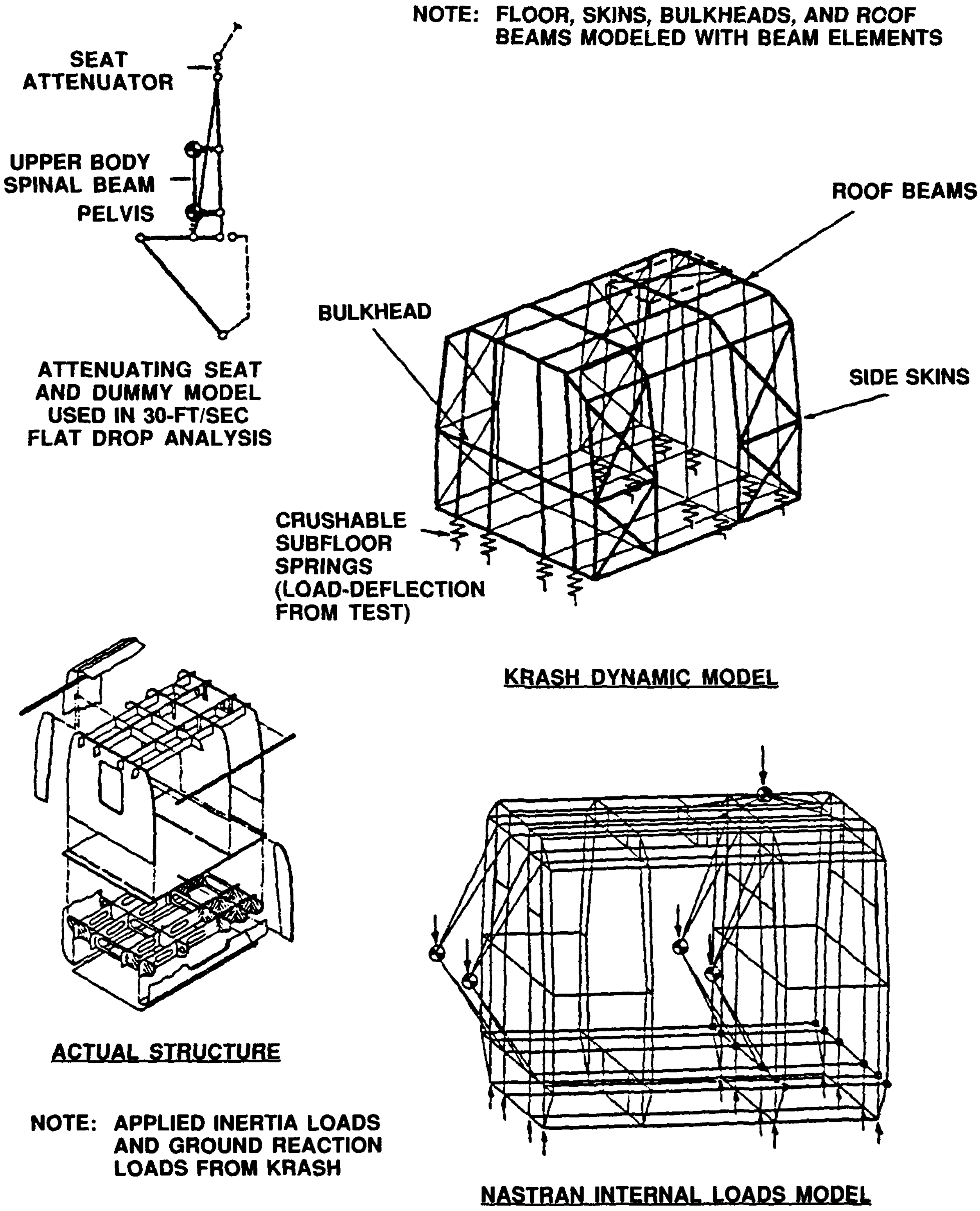


FIG. 9: KRASH AND NASTRAN MODELS OF HELICOPTER COMPOSITE CABIN (REF. 14)

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4 A Review of Crashworthiness of Composite Aircraft Structures

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6 Aeronautical Note

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DESCRIPTORS (KEY WORDS)/MOTS-CLÉS

14
1. Crashworthiness
2. Composite Structures
3. Energy Absorption

SUMMARY/SOMMAIRE

A review of major research activities in North America with respect to the crashworthiness of composite aircraft structures was performed with the goal of identifying potential Canadian contribution to R&D areas where effort would be required to complement the on-going programs in the United States. The areas reviewed included the crashworthiness design criteria of the U.S. Army; major experimental programs undertaken by the FAA, the U.S. Army, NASA, and Bell Helicopter Textron Inc. in the U.S., as well as the University of Toronto in Canada in developing crashworthiness design concepts for composite structures; and the capabilities of crash dynamics computer codes. Recommendations include a study on the effect of aircraft size on crashworthiness design requirements; the implementation of the KRASH code in Canada to establish commonality in analytical methods with major U.S. and European users; an investigation on the energy absorption capabilities of the design features for small aircraft containing composite and/or composite/hybrid structures; and a parametric study on the crashworthiness design of composite-to-composite and composite-to-metal joints.

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